EVALUATING THE IMPACT OF TWO ALLOWABLE PERMISSIVE LEFT-TURN INDICATIONS

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ABSTRACT

National Cooperative Highway Research Program (NCHRP) Report 493 recommended that a flashing yellow arrow (FYA) permissive indication be included in the MUTCD as an alternative option to the circular green (CG). However, as implementation of the FYA permissive indication proceeds, there will be two permissive indications for practitioners to consider at PPLT applications. Using two signal indications which provide drivers with the same message has the potential to increase driver error. Specifically, once drivers are exposed to and understand the meaning of the FYA, it is unclear as to expectancy violations and the likelihood of incorrectly interpretation of the CG as a protected left turn indication.

This research employed a multi-faceted behavioral experiment, including a dynamic driving simulator experiment and computer-based static evaluations to quantify any change in driver comprehension of CG indications resulting from the FYA permissive indication. In the simulator, comprehension of the CG permissive indication following exposure to the FYA permissive indication did not differ significantly from driver comprehension of the CG before exposure to the FYA. In a follow-up static evaluation, drivers exposed to the FYA permissive indication were actually more likely to give yield (correct) responses to the CG permissive indication. In a separate independent static evaluation of one hundred drivers, the breakdown of responses did not differ statistically from responses collected before and after exposure to the FYA. The results provide little evidence to suggest that the FYA implementation will impact driver comprehension of the CG.

Keywords: Protected / Permissive Signal Control, Left-Turns, Driving Simulation, Traffic Operations, Signal Phasing, Solid Yellow Indications

INTRODUCTION

The manner by which left-turning vehicles are accommodated at signalized intersections has evolved over the years; however, the desire for increased capacity and operational efficiency often results in safety-related challenges. A real-world application of this challenge exists within the concept of protected-permissive left turn (PPLT) signal phasing. Recall that PPLT signal phasing provides both a protected phase and a permissive phase all within the same signal cycle, and attempts to balance the competing interests of intersection safety and operational efficiency *(1)*. As a result, PPLT signal phasing has become the focus of myriad research efforts in recent years (*2*-*8*).

National Cooperative Highway Research Program (NCHRP) Report 493 was a comprehensive, national research study to evaluate operational advantages and safety aspects of various left-turn controls at signalized intersections *(2)*. The comprehensive research project, which evaluated all elements of protected/permissive left-turn (PPLT) signal phasing, was based on several identified problems, in particular, the recommended permissive indication *(2)*. In accordance with the Federal Highway Administration's (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD), which provides guidance regarding the use of traffic signal displays, a circular green (CG) indication is the recommended visual message for communicating a permissive left-turn indication to drivers *(9)*. A resulting recommendation of NCHRP Report 493 was that a flashing yellow arrow permissive indication be included in the MUTCD as an alternative option to the circular green permissive indication (see Figure 1 below).

Figure 1 Field installation of the FYA permissive indication.

Background

As a component of previous research efforts, driver comprehension of the most promising types of PPLT signal displays were evaluated (*2, 3*). Using both full-scale fully-interactive driving simulators at the University of Massachusetts at Amherst (UMass) and the Texas Transportation Institute (TTI) as well as a computer-based static evaluation the 12 PPLT signal displays presented in Figure 2 were evaluated. In the driving simulator experiment a total of 3,402 permissive scenarios were evaluated with over 90 percent correct responses. As part of the study, an expanded analysis was completed using incorrect responses, in particular, responses where a driver's error resulted in a crash or near crash event. Note that this type of response is often classified as a fail-critical error (*2, 3, 4*). Among the 12 signal displays evaluated, there was no statistically significant difference in the percentage of fail-critical responses across displays. Nevertheless, there were significant differences in the computer-based static evaluation.

An analysis of incorrect responses from the computer-based static evaluation yielded statistically significant differences across the 12 PPLT signal displays (p = <0.001). Focusing on fail-critical responses, which have the greatest potential of resulting in a crash, Figure 3 presents all of the *go, you have the right-of-way* (fail-critical) responses for all 12 PPLT displays. As shown in Figure 3, a significantly higher number of fail-critical responses are generated from three scenarios. Each of these three scenarios includes the CG permissive indication. Specifically, scenarios two (five-section cluster arrangement, CG permissive indication, and CR through indication), nine (five section vertical, CG permissive indication, and CG through indication), and 10 (five section vertical, CG permissive indication, and CG through indication) were each associated with significantly more *go, you have the right-of-way responses* (*3*).

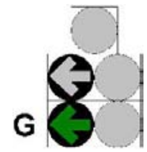
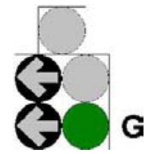
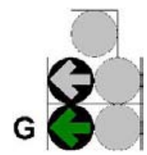
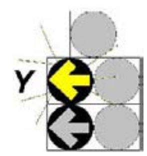
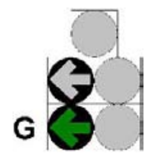
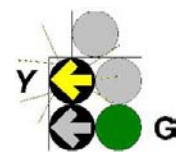
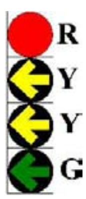
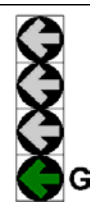
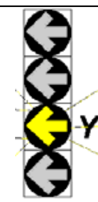
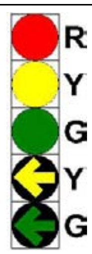
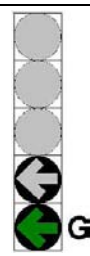
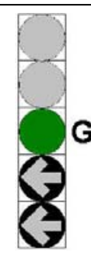
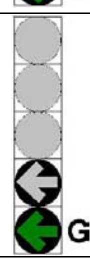
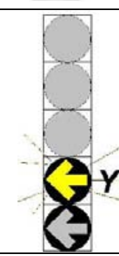
The difference for the findings in the static and simulator evaluations have one simple explanation: drivers in the dynamic simulator environment have more cues available, which provide additional information to assist drivers in making the appropriate left-turn action. Although it is reasonable to believe that the simulator evaluation is more reflective of the real world driving environment, the static evaluation is equally important. Specifically, in the absence of these additional cues, the responses in the static evaluation are indicative of driver's pure comprehension of the permissive indications.

Problem Statement

There are still potential problems in the implementation phase with the FYA permissive indication. In particular, as the implementation of the FYA permissive indication proceeds forward, there will be two permissive indications for practitioners to use with PPLT applications, as recommended in the MUTCD. The use of two signal indications meaning the same thing has been previously show to be problematic and increase the potential to increase driver error (*6*). Specifically, if driver's observe and correctly comprehend the FYA at a series of intersections, and then encounter a CG there may be an impact on their comprehension of the CG permissive indication. There is a need to quantify the impact resulting from a driver having an understanding of the FYA then being "re-exposed" to the CG. To help envision the scenario consider a brief example where a community adopts the FYA and residents there learn the FYA and comprehend it's meaning. Now envision this motorist traveling to a different community and observing a CG; is this driver now likely to interpret the CG as a "go or fail-critical" error because they "know" the FYA means yield. Simply put, if we move forward with the FYA, will it change what drivers believe the CG to mean?

Research is required to determine if drivers are more likely to interpret the CG indication to mean "go" (i.e., protected left turn) if they believe the FYA indication means "yield" (i.e., permissive left turn). This leads to the following hypothesis:

Drivers are more likely to interpret the CG permissive indication to indicate a right-of-way situation if the FYA is gradually implemented at a number of intersections and drivers comprehend the FYA indication.

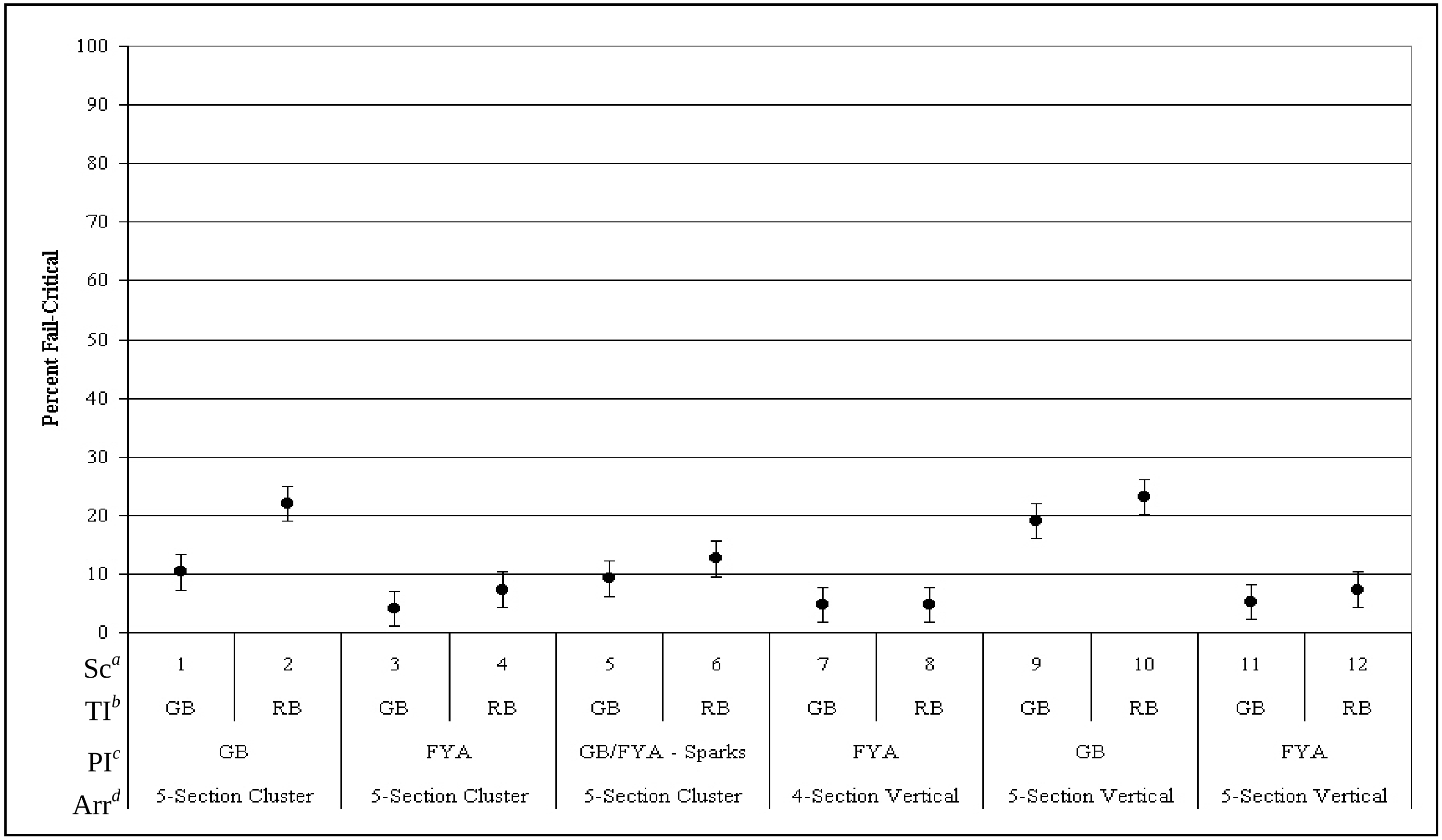
Scenario[a]	Lens Color and Arrangement	Left-Turn Indication[b]	
		Protected Mode	Permitted Mode
1, 2			
3, 4			
5, 6			
7, 8	 O r 	 or 	 or 
9, 10			
11, 12			

R = RED Y = YELLOW G = GREEN *Y* = FLASHING YELLOW

[a] 1, 3, 5, 7, 9, 11 – Green Ball (GB)through indication; 2, 4, 6, 8, 10, 12 – Red Ball (RB) through indication

[b] The indication illuminated for the given mode is identified by the color letter

Figure 2 PPLT displays evaluated in NCHRP Report 493 (*2*).



[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = circular green ball; RB = circular red ball)
[c] Left-turn permissive indication (CG = circular green ball ; FYA = flashing yellow arrow)
[d] PPLT signal display arrangement

Figure 3 Percent of Fail-Critical Responses (with 95 percent C.I.) for Static Evaluation (*2*).

EXPERIMENTAL METHODOLOGY

A multi-faceted behavioral experiment was developed to evaluate the potential impact of the gradual implementation of the FYA permissive indication on driver's comprehension of the CG permissive indication. To evaluate this potential impact, both a dynamic driving simulator experiment and computer-based static evaluation were created. The static evaluation was administered to two different groups: a follow-up static evaluation was completed by all drivers participating in the simulator experiment, and a separate pool of drivers completed the static evaluation, independently of the driving simulator experiment (referred to herein as the independent static evaluation). An overview of the research approach is presented in Figure 4.

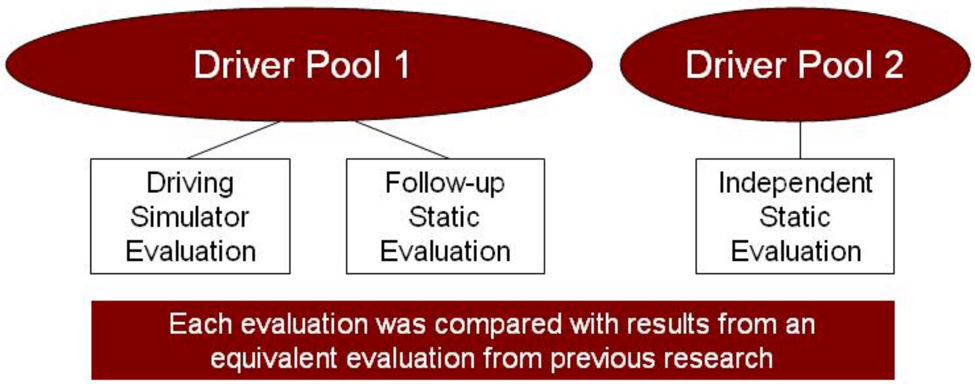


Figure 4 Overview of research process.

To assess the impact on driver comprehension result from each of the three evaluations (simulator, follow-up static, and independent static) were compared with results from identical studies in a preceding experiment. The rational here was that in previous research drivers evaluating a CG had not been exposed to (i.e., learned the meaning of) the FYA permissive indication. In the current studies drivers were trained as to the meaning of the FYA so that the impact of the FYA on driver's perceived meaning of the CG could be quantified. As noted, this scenario would exist if the FYA is adopted into the MUTCD as an allowable permissible indication in addition to the CG permissive indication.

Static Evaluation (Independent and Follow-up)

A computer-based static evaluation was administered to 100 drivers. During the introduction to the static evaluation, drivers were *trained* on the meaning of FYA indication. The training screen, pictured in Figure 4, explained to drivers the meaning of a new traffic signal display: the FYA. Drivers were informed that the new display required them to yield to oncoming traffic and select an appropriate gap in the opposing traffic. Drivers were also instructed as to what the FYA did not imply, namely the FYA did not give them the right-of-way nor does it require them to stop and wait for an appropriate traffic signal indication. As shown in Figure 5, drivers were provided with pictorial examples of the FYA permissive indication as part of the training.

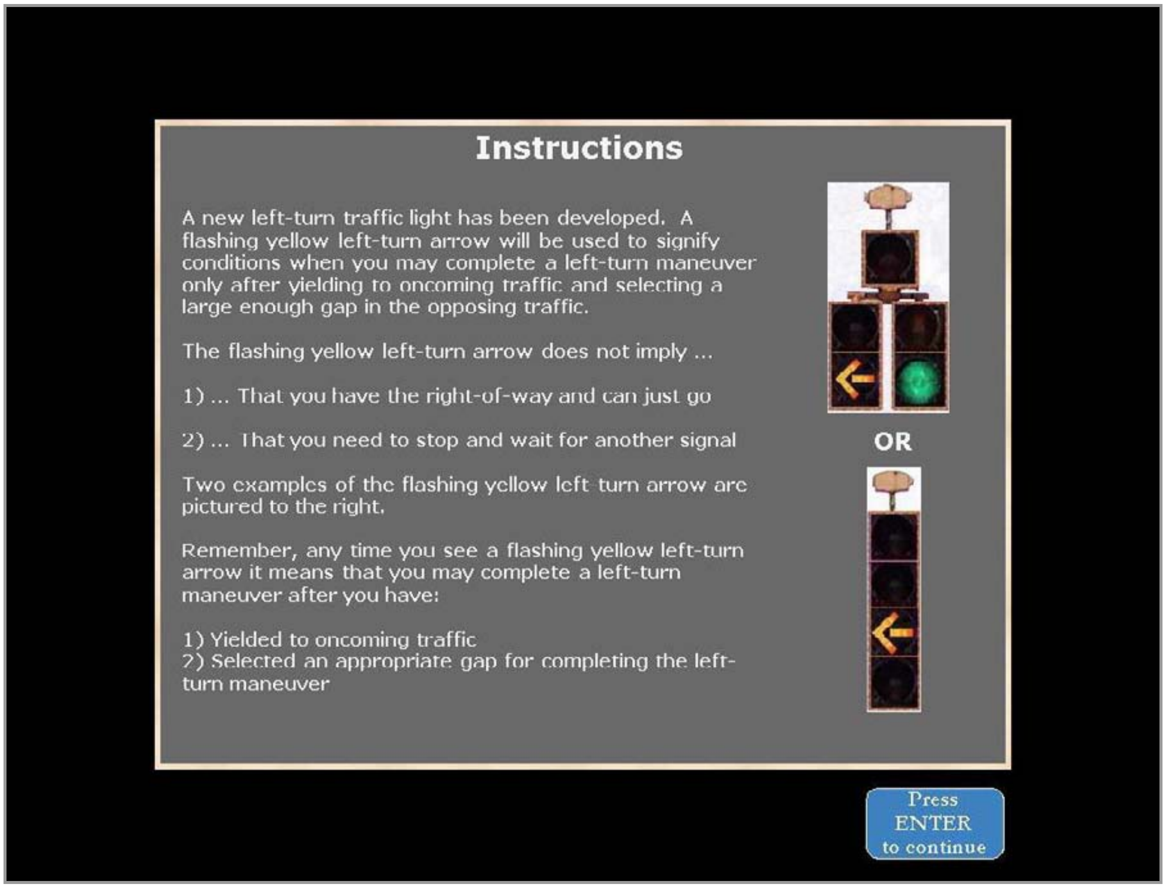


Figure 5 Sample of FYA indication training for static evaluation.

Drivers then observed seven scenarios in the static format displaying either a FYA permissive indication (5 scenarios) or GA protected indication (2 scenarios). Each time driver's were asked to respond to the following question with the appropriate response:

"If you want to turn left and you see the traffic signal lights shown, you would?"

- Go, you have the right-of way;
- Yield, then go if a gap in the opposing traffic exists;
- Stop, then go if a gap in the opposing traffic exists; or,
- Stop and wait for the appropriate signal.

This format is consistent with previous research efforts. On the final scenario in the static evaluation, drivers observed a CG permissive indication, and were again asked what they would do given their perceived desire to make a left-turn maneuver as presented in Figure 6.

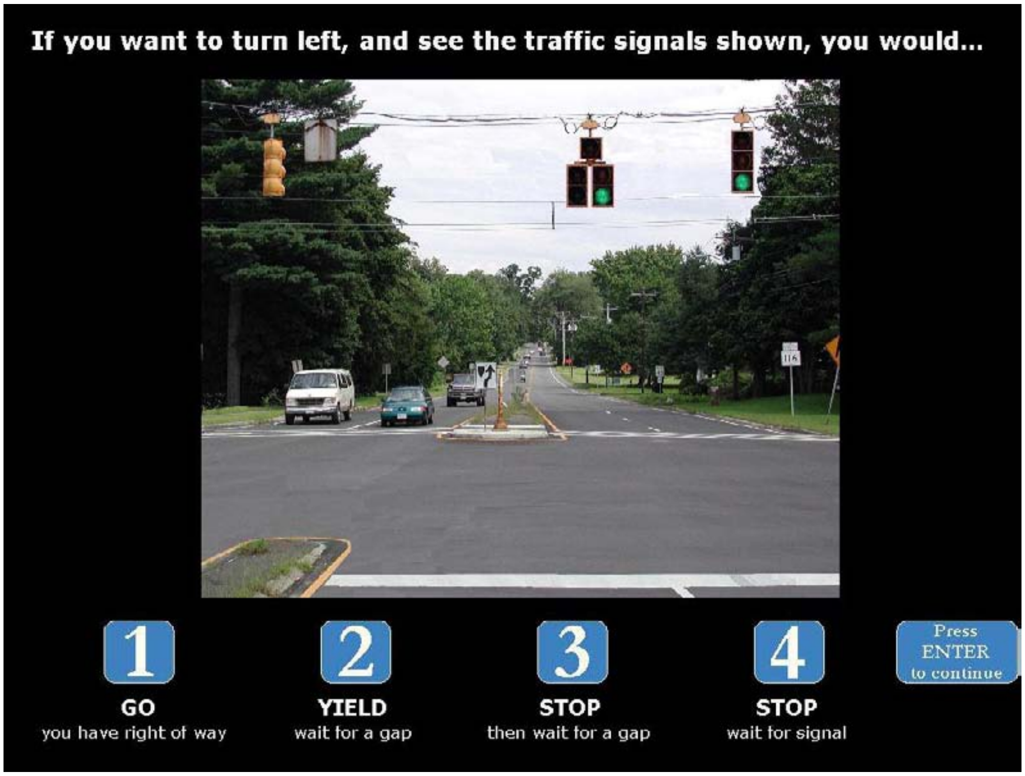


Figure 6 Final scenario presented to drivers featuring circular green permissive indication.

Driving Simulator Experiment

A similar approach was used to conduct the driving simulator experiment, completed by a total of 25 drivers, in the Human Performance Laboratory (HPL) at UMass. The driving simulator used was a full-scale, fixed-base fully-interactive 1995 Saturn sedan. Drivers were capable of controlling the steering, braking, and accelerating similar to the actual driving process; the visual roadway adjusted accordingly to the driver's actions. The visual field-of-view, which subtends 150-degrees, was projected by three separate images in a semi-circular fashion. The HPL driving simulator is pictured in Figure 7.

Figure 7 UMass Human Performance Laboratory driving simulator.

Simulated Environment

An innovative research approach was employed in this research experiment. A virtual network of intersections was initially created along with the algorithms necessary to control the simulated driver-vehicle interactions. Each of these features were integrated within the driving simulation visual world to replicate an actual driving environment for experimentation.

Before being seated in the simulator, drivers were trained about the FYA using the computer-based training page (Figure 4). Drivers then completed one driving module with 14 total intersections with seven left-turn intersections containing either a FYA permissive indication or protected green arrow indication. This format was consistent with the approach used in the computer-based static evaluation. Following the seventh intersection, drivers traversed a long rural segment in the simulator environment. The intent of this rural segment was to replicate drivers transitioning from one municipality to an abutting jurisdiction. Following this segment, drivers encountered another left-turn intersection featuring only a CG permissive indication, which is presented in Figure 8. The operational characteristics were consistent with those used in previous research efforts (*2, 3, 4*). Specifically, as each driver approached the intersection the signal displays was all-red and opposing vehicles were queued at the opposing stop bar. An algorithm was developed such that the visual placement of the vehicle led to the automated changing of the traffic signal indication to the CG permissive indication and the opposing traffic was released. After completing the simulator portion each driver also went on to complete the static evaluation described previously (referred to as follow-up static evaluation).

Figure 8 Screen capture of final scenario (CG permissive indication) in driving simulator.

Recording Driver Responses

Driver comprehension was based on driver's responses at each of the experimental intersections. Correct responses were recorded based upon drivers yielding the right-of-way. Note that the presence of the initially queued opposing traffic forced drivers to make a decision as to the correct response. For the CG scenario the correct response was for drivers to yield to the opposing traffic stream before completing the left-turn maneuver. Incorrect maneuvers/responses were classified as fail-safe or fail-critical in a manner consistent with previous research (*2*, *3*, *4*). A fail-safe response is one in which the driver did not correctly respond to the signal display arrangement/permissive indication combination, yet did not infringe on the right-of-way of opposing traffic. A fail-critical response was an incorrect response in which the driver incorrectly responded to the signal display and impeded the right-of-way of opposing traffic, thus creating the potential for a crash.

Experimental Results and Data Analysis

Driver comprehension was determined from the distribution of correct and incorrect responses. The resulting data from the dynamic and static evaluations consisted of the following:

- Distribution of correct and incorrect responses for the PPLT signal display with the CG permissive indication from the static evaluation; and
- Distribution of correct and incorrect responses for the PPLT signal display with the CG permissive indication from both the driving simulator experiment and follow-up static evaluation.

To study the impact on driver comprehension of the CG permissive indication, the results from each of these studies were compared first with each other, using a chi-square analysis. Then to determine potential changes in CG driver comprehension the results were statistically compared with those of previous research (*4*). The comparison is appropriate, as drivers completing the initial driving simulator experiment had not received training as to the meaning of the FYA permissive indication, which differs from previous research. A chi-square analysis was used to complete the analysis, and appropriate measures were taken to make sure dynamic simulator data were compared to dynamic simulator data from other studies. Similarly, static data from this experiment were compared with static findings from other studies.

RESEARCH RESULTS

A total of 25 drivers participated in the driving simulator experiment and follow-up static evaluation, while 100 drivers participated in the independent static evaluation. A summary of the research participants for each of the evaluations are presented in Table 1. In total, 150 permissive left-turn scenarios were evaluated in the driving simulator, 175 were evaluated in the follow-up static evaluation, and 700 PPLT scenarios were evaluated in the independent static evaluation. The sample of drivers participating in the independent static evaluation are representative of the driving population in Massachusetts and comparable states. The sample size in the simulator and follow-up static evaluations did not allow for the disaggregating of demographic variables while still allowing for appropriate statistical comparisons. Although previous research on the subject has indicated little difference across driver ages in the simulator environment, any potential effects resulting from the younger sample cannot be interpreted in the current study *(2-5).*

Table 1 Summary of Driver Demographics

		Simulator and Follow-Up Static		**Independent Static**	
Category	**Level**	**No. of Drivers**	**% of Total[a]**	**No. of Drivers**	**% of Total[b]**
Gender	Male	17	68	50	50
	Female	8	32	50	50
Age	Under 25	12	48	29	29
	25 to 44	12	48	38	38
	Over 44	1	4	33	33
Annual Miles Driven	Under 10,000	9	36	31	31
	10,000 to 20,000	10	40	39	39
	Over 20,000	6	24	30	30

[a] Percent of sample based on 25 drivers in simulator evaluation
[b] Percent of sample based on 100 drivers in independent static evaluation

Driving Simulator and Follow-Up Static Evaluation Results

To quantify the impact of the FYA permissive indication on driver comprehension of the CG, the breakdown of driver responses was compared with this breakdown from an equivalent driving simulator experiment completed previously. As mentioned, the comparison is appropriate, as drivers completing the initial driving simulator experiment had not received training as to the meaning of the FYA permissive indication. Furthermore, the studies were equivalent in nature, and even used the same testing materials. Figure 9 presents the comparison of simulator responses at the CG scenario from each of these driving simulator experiments. Of the 49 responses from the initial driving simulator experiment, there were no fail-critical (*go*) responses, six instances where drivers allowed all opposing traffic to pass, and three instances in which drivers had to be directed to proceed. Statistically, the breakdown of driver responses from the two simulator experiments did not differ significantly (p = 0.456).

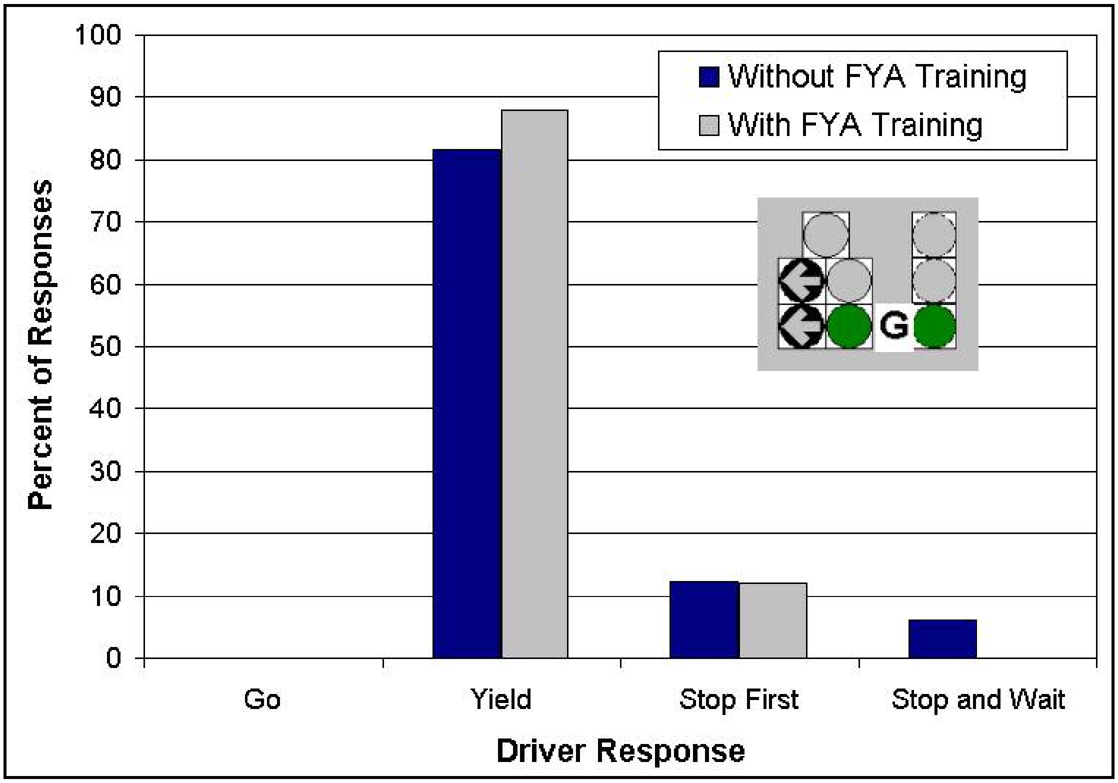


Figure 9 Breakdown of driver responses at CG permissive indication scenario in driving simulator experiment with and without FYA training.

A comparison of driver responses from the CG scenario in the follow-up static evaluation from this analysis as well as the follow-up static evaluation from an equivalent experiment was completed as shown in Figure 10. The difference in *yield* responses was statistically significant (p = 0.033) with more drivers responding *yield* at the CG scenario after having had FYA training. Nevertheless, when the *yield* and *stop first* responses are both considered as correct responses, the percentage of correct responses was 83 percent (45 of 54 responses) without FYA training and 92 percent (23 of 25 responses) when drivers had received FYA training; however, this difference is not statistically significant (p = 0.307).

A direct comparison of incorrect responses from the simulator and follow-up static evaluation was completed for the CG scenario. The one driver responding *go* in the follow-up static evaluation had responded correctly in the simulator. Similarly, the driver that responded *stop and wait* in the follow-up static evaluation had responded correctly in the simulator experiment. Finally, of the three drivers that allowed all opposing vehicles to pass in the simulator experiment before completing their left-turn maneuver, one later responded *stop first* in the follow-up static, while the other two drivers later responded correctly.

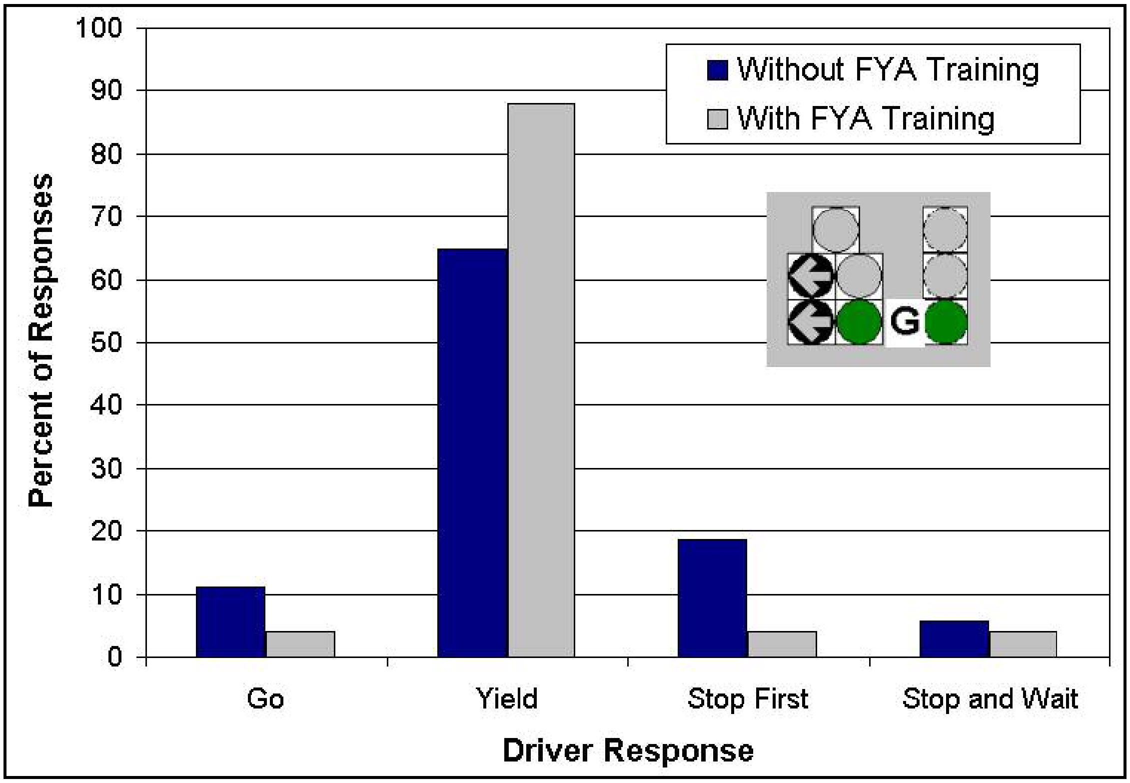


Figure 10 Breakdown of driver responses at CG permissive indication scenario in follow-up static evaluation with and without FYA training.

Independent Static Evaluation Results

Each of the 100 participating drivers were initially presented with a FYA training scenario as previously presented in Figure 5. Drivers then responded to eight scenarios featuring either the green arrow or some combination of the FYA permissive indication. The CG scenario (Scenario #7, shown in Figure 6) was consistently the final scenario presented to drivers. Driver responses at the CG scenario following FYA training were compared with the breakdown of responses from another independent static evaluation from a previous research effort. A comparison of the responses is presented in Figure 11 - the differences between the two distributions of responses were not statistically significant ($p = 0.289$).

An additional comparison was made between driver responses for scenarios with the FYA permissive indication before and after FYA training. The breakdown of responses before and after is presented for each of several FYA scenarios, which have been the focus of previous research efforts, in Figures 12 to 15 (*2*, *3*, *4*). The percentage of yield responses increased following FYA training with the exception of the CR/FYA scenario. The difference in yield responses was statistically significant for both FYA scenarios which featured an adjacent through movement CG indication ($p = 0.026$ and $p = 0.001$), however the distribution of responses with adjacent through movement CR indications did not differ statistically ($p = 0.589$ and $p = 0.280$, respectively). It could be mentioned that for the configurations with a Circular red indication showing (i.e. Figure 14 and 15) one might expect more "stop" responses, since a circular red indication typically means stop.

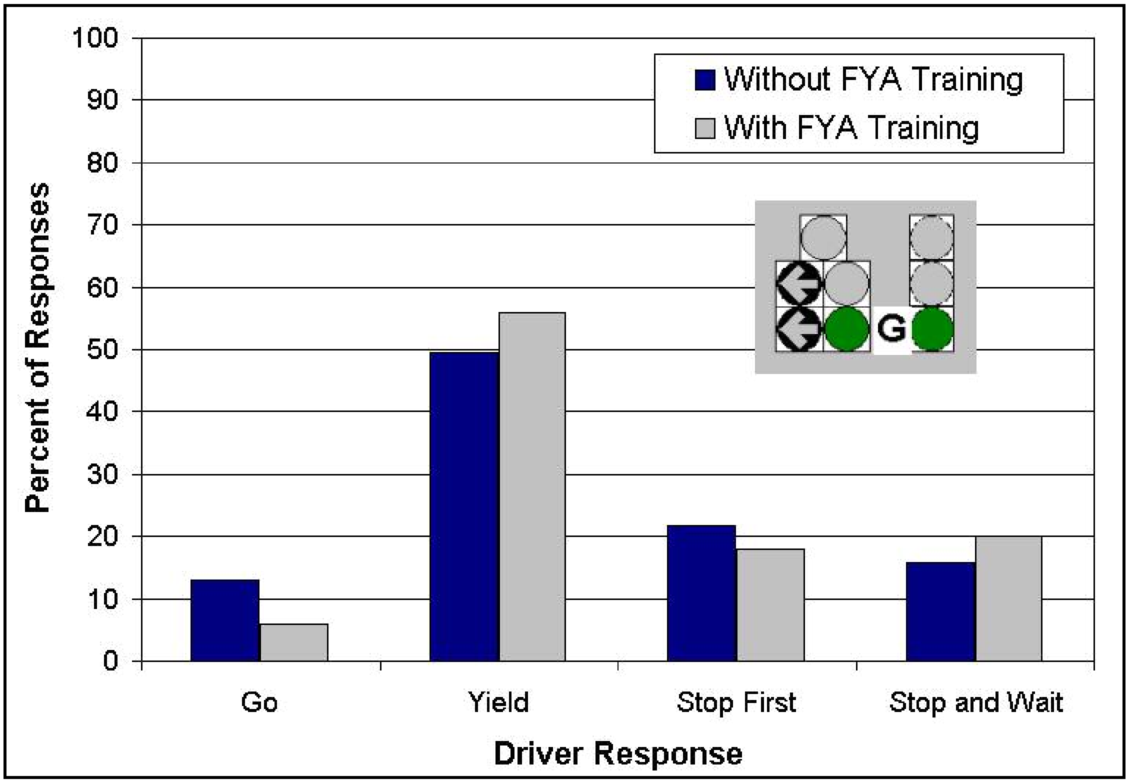


Figure 11 Breakdown of driver responses at CG permissive indication scenario in independent static evaluation with and without FYA training.

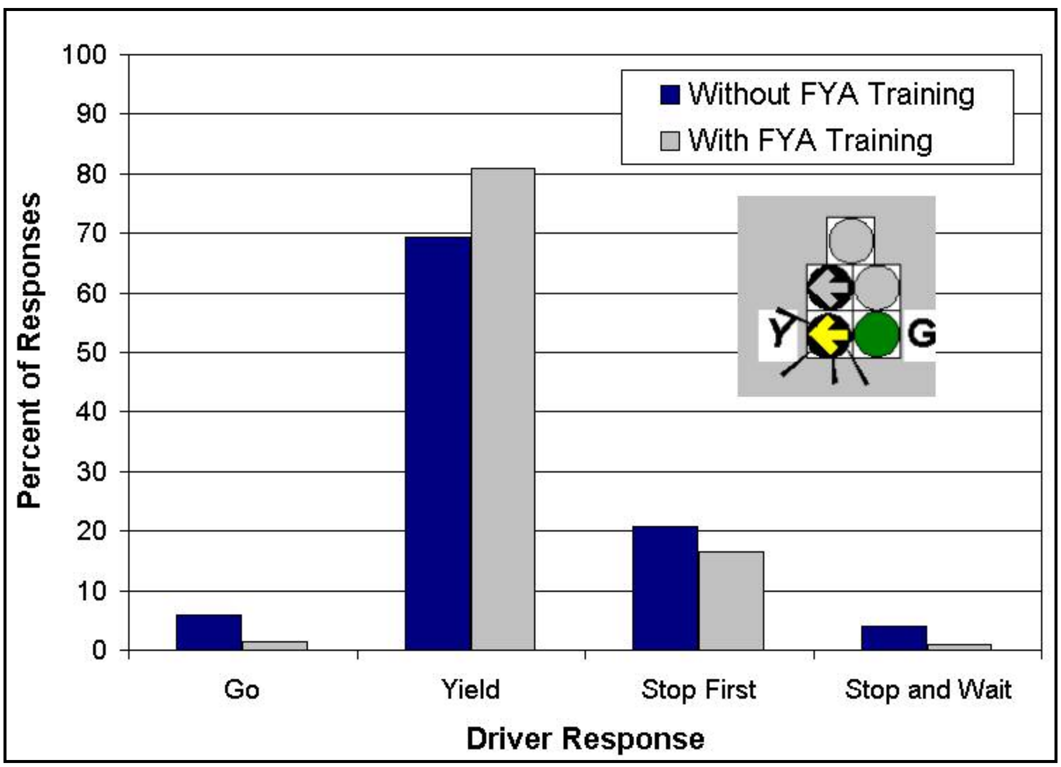


Figure 12 Breakdown of responses at FYA/CG permissive indication scenario in independent static evaluation with and without FYA training.

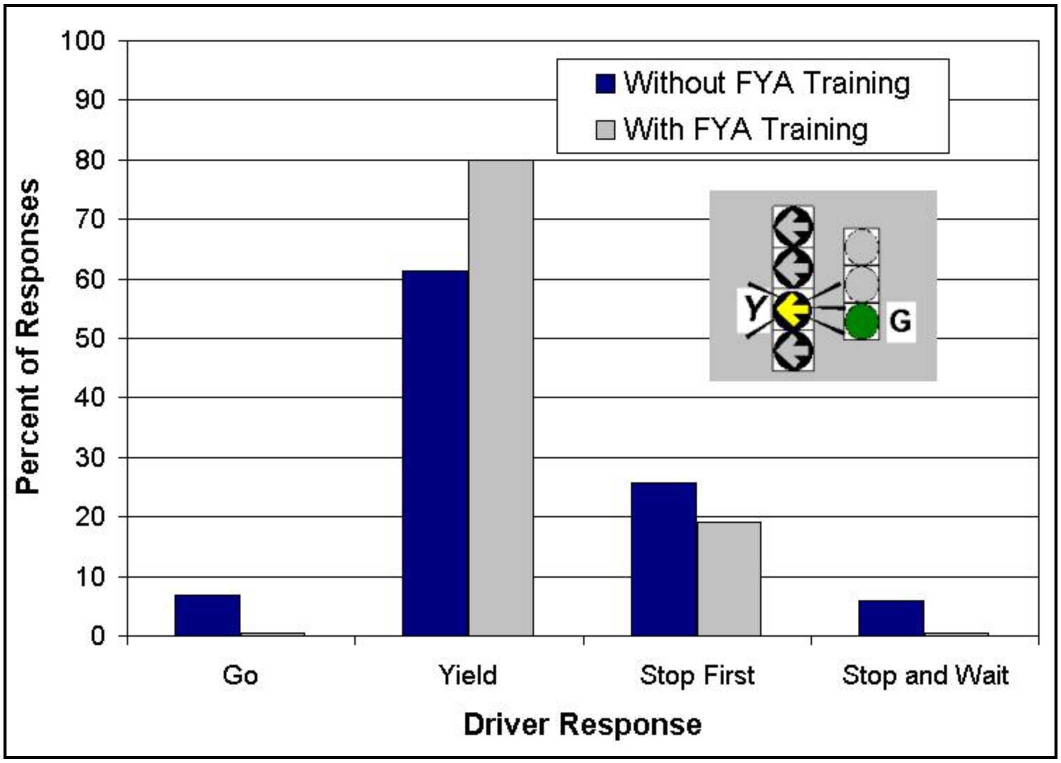


Figure 13 Breakdown of responses at FYA permissive indication with adjacent CG scenario in independent static evaluation with and without FYA training.

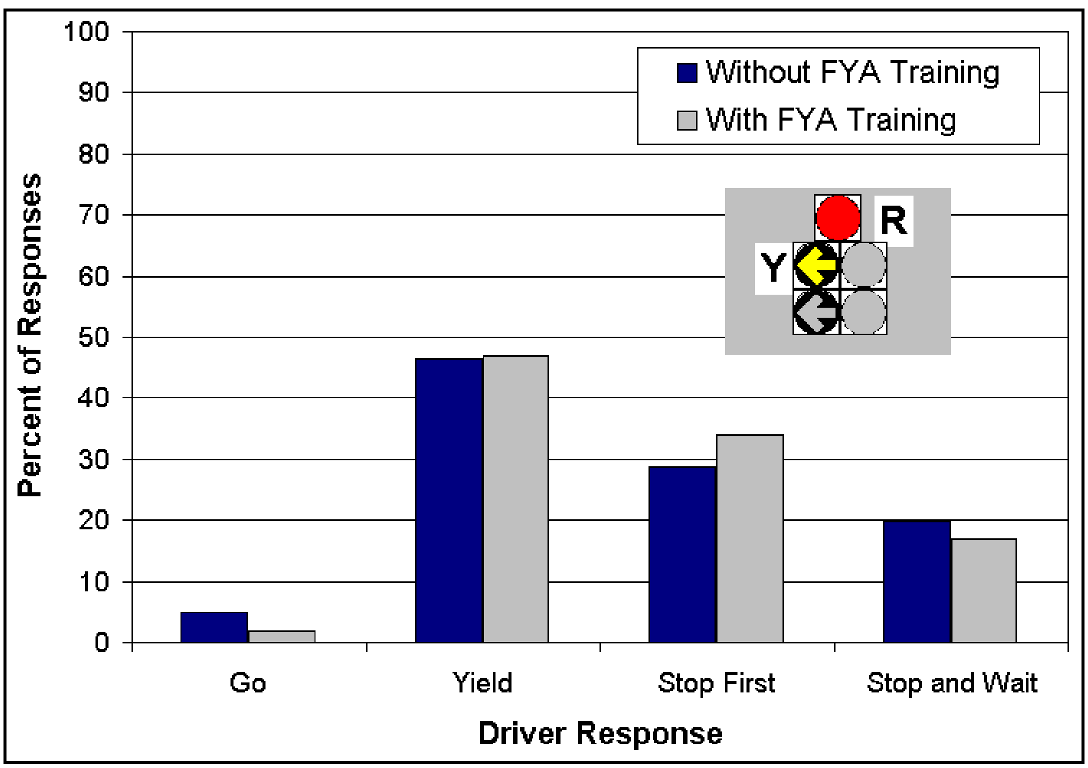


Figure 14 Breakdown of Responses at FYA/CR Permissive Indication in Independent Static Evaluation With and Without FYA Training.

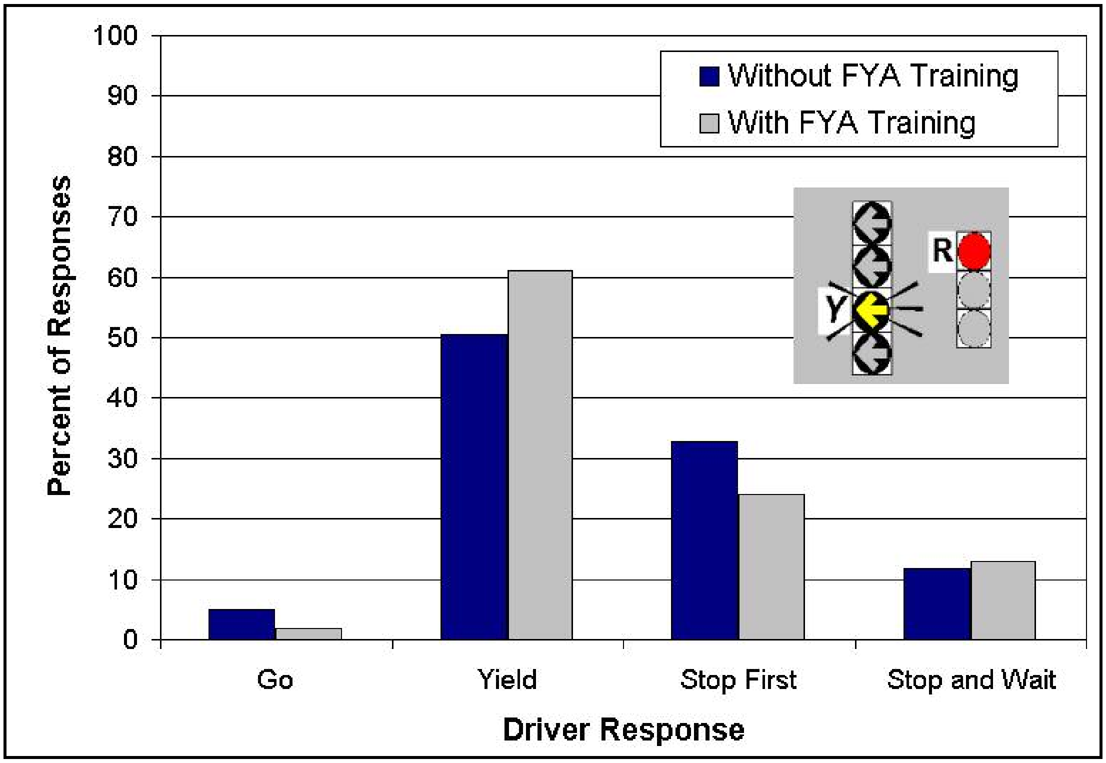


Figure 15 Breakdown of responses at FYA permissive indication with adjacent CR scenario in independent static evaluation with and without FYA training.

CONCLUSIONS AND RECOMMENDATIONS

This analysis was designed to quantify the impacts of the gradual implementation of FYA permissive indications on driver comprehension of the CG permissive indication. Specifically, if drivers are exposed to, comprehend, and develop expectancy in the FYA as a permissive left-turn indication, how is their comprehension of the CG permissive indication (and associated behavior) affected if traveling through a location that has not implemented the FYA? Using a driving simulator experiment, follow-up static evaluation, and an independent static evaluation, several significant findings were discovered, including the following:

- In the driving simulator, driver comprehension of the CG permissive indication following exposure to the FYA permissive indication did not differ significantly from driver comprehension of the CG before exposure to the FYA in the driving simulator. To complete this analysis the comparison is between responses of drivers in the previous simulator experiments who had not been previously exposed to the FYA permissive indication versus drivers who have been trained regarding the FYA (current experiment).
- In the follow-up static evaluation, drivers who had been exposed to the FYA permissive indication were significantly more likely to give yield responses to the CG permissive indication.
- In the driving simulator, no fail-critical responses were observed at the last CG scenario, and only one *go* response (four percent) was reported in the follow-up static evaluation completed immediately following the simulation.
- In an independent static evaluation of one hundred drivers, the breakdown of responses did not differ statistically from responses collected similarly in previous research.

The data do not support the tested research hypothesis that *drivers are more likely to interpret the CG permissive indication to indicate a right-of-way situation if the FYA is gradually implemented at a number of intersections and drivers comprehend the FYA indication*. Specifically, data obtained after drivers had been exposed to the FYA were statistically equivalent to drivers' comprehension of the CG before exposure to the FYA. In fact, there is evidence to suggest that driver training of yield requirements in general may prove beneficial to drivers as more drivers responded yield after learning the definition of a yield maneuver in general. There is still a need to consider the potential violations of driver expectancy resulting from partial implementation of the FYA permissive indication, as the drivers participating in this experiment were only exposed to the FYA during the course of the experiment, and it is reasonable to assume that the impact may be different if the exposure spans a longer period of time.

This research also provided initial evidence regarding the potential impact of future FYA training efforts. Interestingly, the two scenarios pictured as examples were associated with higher percentage of correct responses after FYA training than all other FYA scenarios not pictured in the training which may indicate the potential for future FYA training. .

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